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The influence of climatic changes on the groundwater resources and reserves in Slovakia

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Abstract. This paper provides an assessment of the quantitative groundwater resource changes due to climatic changes in Slovakia during the last two decades. This decrease in available groundwater resources was first noted in the period 1981 - 1985. The following 5-year period s show larger decreases in much of Slovakia

Comparison of the groundwater yield of this significantly affected period with the unaffected period prior the year 1980 have been done.

An attempt of prognosis of this serious changes to the year 2010 is presented too.

Using pre - 1981 as reference period, the subsequent decreases in groundwater resources availability are: 1981 - 1985, 6.7%; 1986 - 1990, 19.5 %; and 1991 1995, 20.2 %. While this decreases of as much as 20 % cover much of Slovakia, they even reached 40 % in the southern part of the country during 1986 - 1995.

Keywords: groundwater resources, climatic changes, decrease of groundwater yield, temporal changes, spatial changes.

Introduction

This paper presents an evaluation of quantitative changes in the groundwater resources and reserves in Slovakia, which are believed to be caused by significant changes in the climate factors during the last decades. The main aim of this study is to provide a quantitative comparison of spring discharge of groundwater during a period that was not significantly influenced by the climatic changes with the present groundwater discharge. From the evaluated data a prognosis to the year 2010 is offered.

This study is part of a larger program, known as "PHARE No. EU/95/WAT/31: The Evaluation of Groundwater Resources in Slovak Republic", initiated and supervised by the Ministry of the Environment of the Slovak Republic and carried out during 1996–1997 by the Irish firm of PM Consulting Engineers, Dublin, in the co-operation with Slovak experts and SHMÚ Bratislava. The present study also covers some results from a detailed evaluation of climatic changes and its influence on the groundwater resources and reserves in the Mesozoic formations of the mountain ranges of Slovenský raj and Havranie vrchy (Kullman, 1998).

Previous studies on these topics were made by Chalupka J. & Kullman E., 1992; Kullman E. & Chalupka J., 1995; Fendeková M. et al. 1995; and Kullman E. Jr. et a.l 1995.

The evaluation of the influence of the changes of climatic factors on groundwater regime in Slovakia

The timing of the onset of decrease in groundwater availability in Slovakia and that of climatic change are vital in proposing a casual relationship.

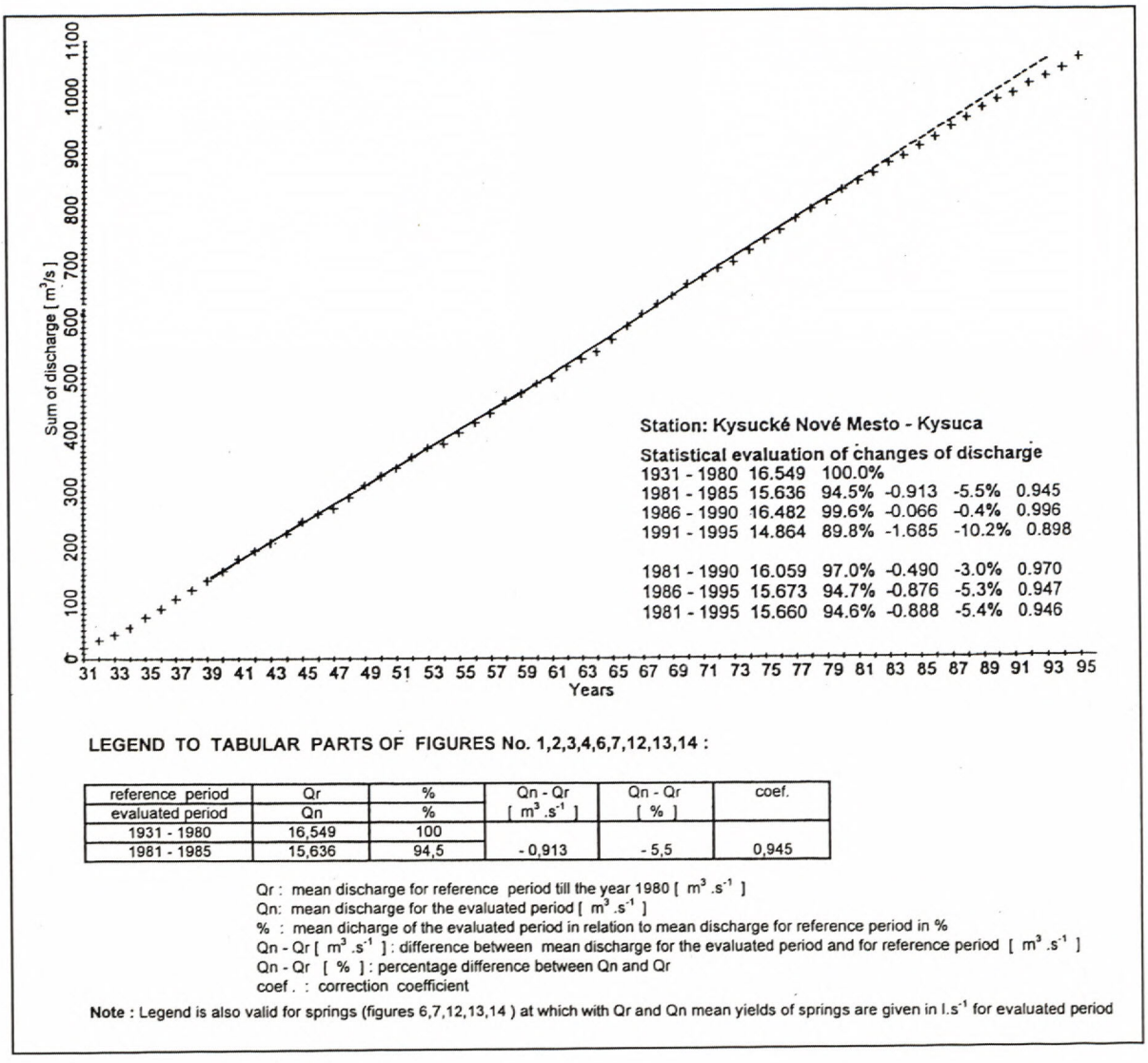
The recent results of the studies carried out by the Slovak climatologists, hydrologists and hydrogeologists were utilised for this solution and these were supported by comprehensive data evaluations in the sphere of the groundwater monitoring which enabled to resolve the commencement of recorded influence of significant climatic changes on groundwater.

Climate data for the period 1951–1980 (Lapin & Faško, 1996) are useful in providing a reference base pre - dating the onset of climatic change. The records from 29 precipitation stations show that there were no significant changes (only 0.44 %) in the annual precipitation between the periods 1931–1960 and 1931–1980 (Majerčáková & Šedík, 1994). Therefore the period 1961 - 1980 could be used as a reference period for the other data.

The data obtained from 36 discharge gauging stations (Majerčáková & Šedík, 1994) also show only 1.6 % decline in average discharge from the periods 1931–1960. This data is presented on Tab. 1 and by the cumulative diagrams of mean annual discharges from different parts of Slovakia (Fig. 1,2,3,4).

The groundwater data series in Slovakia is substantially shorter than those for precipitation and surface water discharge. For the evaluation of the documented groundwater resources and reserves changes we used :

1. A long-term 90 – year data series of groundwater level fluctuation monitored in the borehole V-10 Banín (Svitavy region, Czech Republic), with the period of observation from 1901 to 1990 (the longest grundwater observation series in the former Czechoslovakia). The results of average annual levels to 1980 also show the preceding evaluations, i.e. sustained stability of the mean annual levels during the period of 1901–1980 (Fig. 5).



LEGEND TO TABULAR PARTS OF FIGURES No. 1,2,3,4,6,7,12,13,14 :

reference period / evaluated period	Qr / Qn	% / %	Qn - Qr [$m^3.s^{-1}$]	Qn - Qr [%]	coef.
1931 - 1980	16,549	100			
1981 - 1985	15,636	94,5	- 0,913	- 5,5	0,945

Qr : mean discharge for reference period till the year 1980 [$m^3.s^{-1}$]
Qn: mean discharge for the evaluated period [$m^3.s^{-1}$]
% : mean dicharge of the evaluated period in relation to mean discharge for reference period in %
Qn - Qr [$m^3.s^{-1}$] : difference between mean discharge for the evaluated period and for reference period [$m^3.s^{-1}$]
Qn - Qr [%] : percentage difference between Qn and Qr
coef . : correction coefficient

Note : Legend is also valid for springs (figures 6,7,12,13,14) at which with Qr and Qn mean yields of springs are given in $l.s^{-1}$ for evaluated period

Fig. 1 Location: Kysucké Nové Mesto; station no.: 6200, river: Kysuca

2. The preceding results are also shown by the cumulative diagrams of evaluated springs discharge and groundwater levels in the monitoring wells, although based on a shorter series of observations. As illustrated by the cumulative diagrams of springs No.1966 and 1901 (Fig. 6 and 7). These also document the possibility of using a shorter series of observations prior year 1981 as representative of the reference period. The cumulative diagrams of spring discharge and groundwater levels in the monitoring wells may confirm this claim.

The presented set of evaluations indicate that:

- *The hydrological regime, both in the sphere of surface runoff and in the sphere of groundwater up to 1980 was not influenced, alternatively, negligibly influenced by climatic changes.*
- *From the hydrological point of view the possibility to consider the period up to 1980 as the period which was not significantly influenced by climatic changes and in this way suitable as the reference period for the evaluation of groundwater resources and reserves in the period from 1981 to 1995.*
- *With regards to the stability of hydrological regime up to 1980 (mainly in the period 1941–1980) the possibility to consider with full responsibility even relatively short evaluations up to 1980 as the reference periods for assessing the changes of groundwater resources and reserves due to climatic factors changes after year 1980.*
- *Notable changes in hydrological regime and in this way also significant quantitative changes in groundwater resources and reserves began to appear in Slovakia, in a significant degree, according to these evaluations, only after the year 1980, while the period from 1981–1985 can be considered as the beginning of the period with a fast and adverse , even very disastrous negative changes for water management.*

The implementation of quantitative changes evaluation in groundwater resources and reserves due to climatic factors changes

From the whole data set of continual monitoring of spring yields and from the selection of data on ground

Table 1 Evaluation the discharge during the periods 1931–1980 and 1981–1995 in relation to the reference period for selected rivers (compiled by E. Kullman using results of O. Majercakova, 1994)

Gauging station No.	Location stream	Monitoring period	Reference period mean annual discharge $Q\ (m^3 . s^{-1})$ – 100 %	Percentile changes in relation to reference period						
		Number of years		1951–1980	1961–1980	1971–1980	1981–1985	1986–1990	1991–1995	1981–1995
6200	Kysucké Nové Mesto Kysuca	1931–1995 65	1931–1980 16,549	+1,4	+3,4	+2,3	–5,5	–0,4	–10,2	–5,4
5340	Kráľova Lehota Bôca	1931–1995 65	1931–1980 2,214	–3,7	–4,3	–6,1	–18,5	–30,4	–23,6	–24,1
6950	Zlatno Hron	1931–1995 65	1931–1980 1,551	–3,0	–4,2	–4,5	–15,6	–35,6	–23,6	–24,9
8970	Nižný Medzev Bodva	1941–1995 55	1941–1980 0,940	+2,1	–4,6	–3,4	–7,2	–53,3	–42,5	–34,3

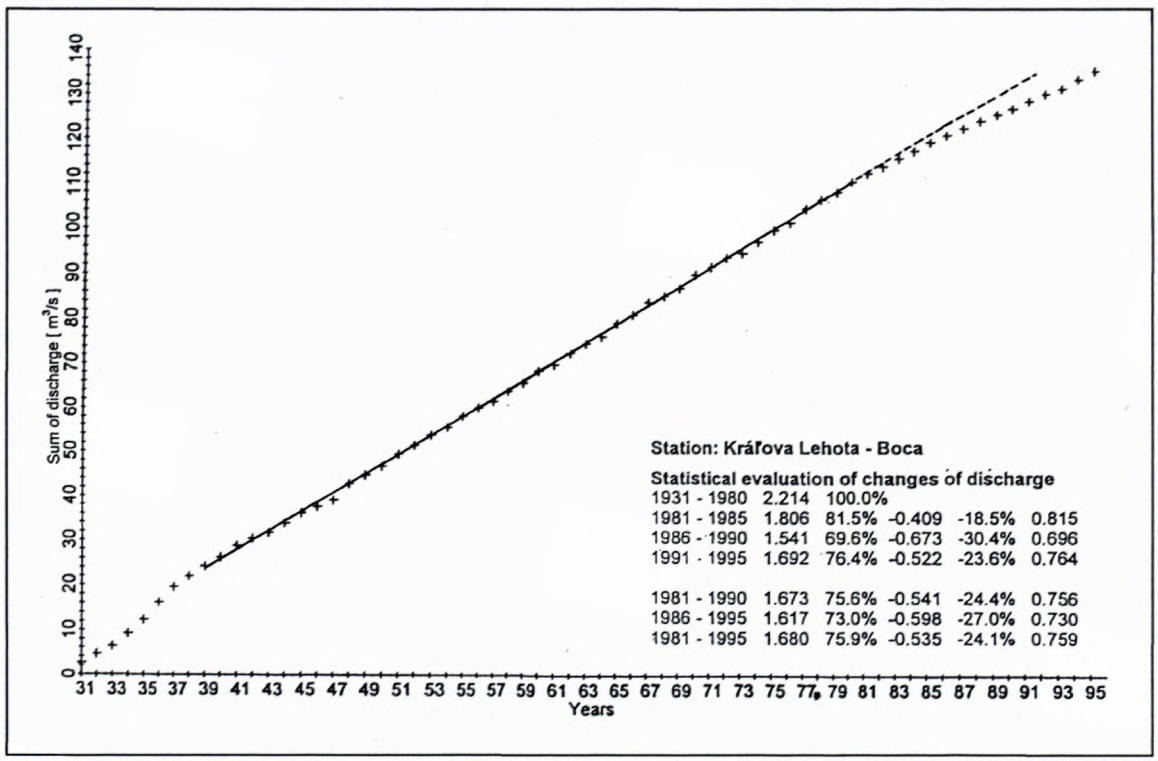


Fig. 2 Location: Kráľova Lehota; station No.: 5340, river: Boca

water levels in the monitoring wells (on the territories of south-western and southern Slovakia, without existence, or with small occurrence of springs) carried out by SHMÚ Bratislava, for evaluation were chosen the longest observation sets from 1956 to 1974 (in the small extent from 1975 to 1976). After data verification from the point of view of homogeneity, a collection of 82 long-term sets of spring yields observations and collection of 18 long-term sets of groundwater level observations in the monitoring wells were selected for evaluation.

In this selected collection were assessed quantitative changes in groundwater resources and reserves in the period 1981–1995 by the comparative method using the values from the period before 1981, which according to climatic and hydrologic knowledge was without significant changes at least in the period 1941–1980. In this period was not documented any influence or negligible influence of climatic changes on the groundwater resources and reserves.

The cumulative diagrams of mean annual spring yields or mean annual levels (in levels from differences H_{max}-H) were constructed for the evaluation of long-term sets of data. The constructed cumulative diagrams enable to assess the course of mean annual yield changes and the changes in mean annual levels of groundwater during the whole evaluation period. These also show time when

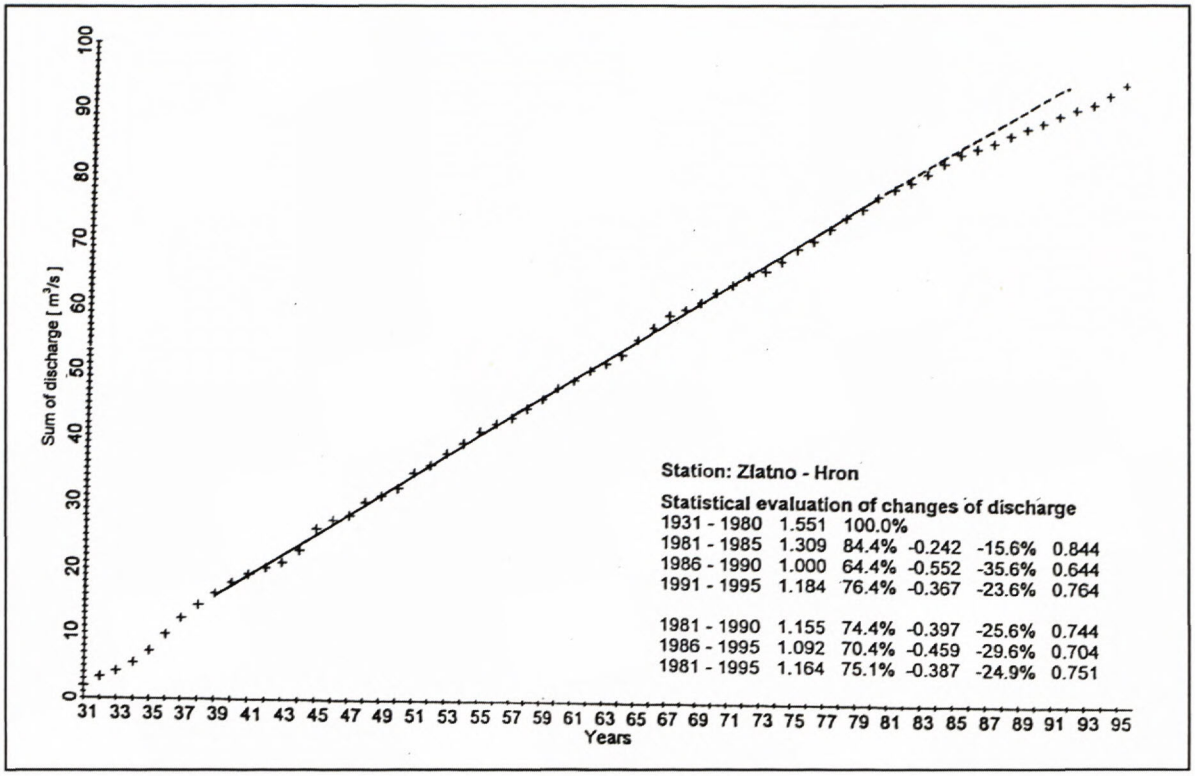


Fig. 3 Location: Zlatno; station No.: 6950, river: Hron

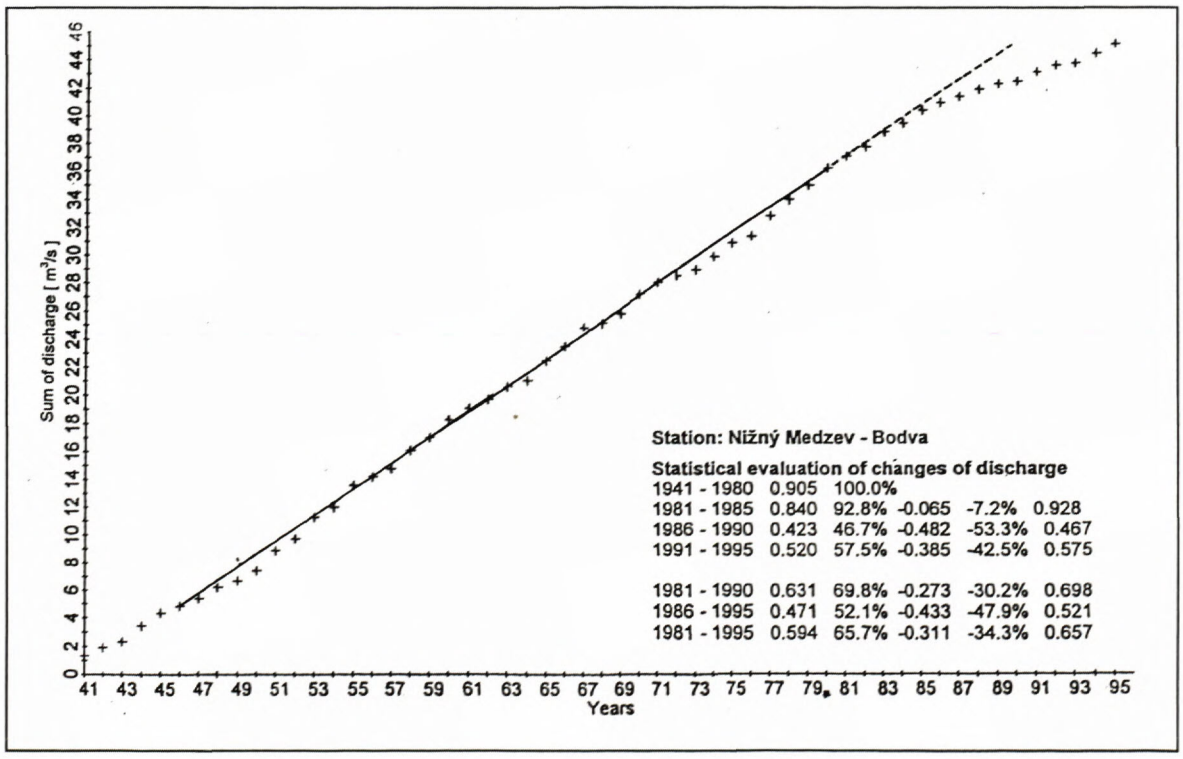


Fig. 4 Location: Nižný Medzev; station No. 8970, river: Bodva

prominent quantitative changes started as well as the course of these changes in the period 1981–1995. For quantitative assessment of the changes were enumerated average values for 5 – year periods and for the whole period 1981–1995. This values show the difference with regard to the reference period in individual evaluated resources, in average in individual geomorphological unit, as well as, in larger territories of Slovakia.

The prognosis of quantitative changes of groundwater resources up to 2010 was also one part of the evaluation. A prognosis is always a very complicated problem and it must be set on certain, although unverified assumptions.

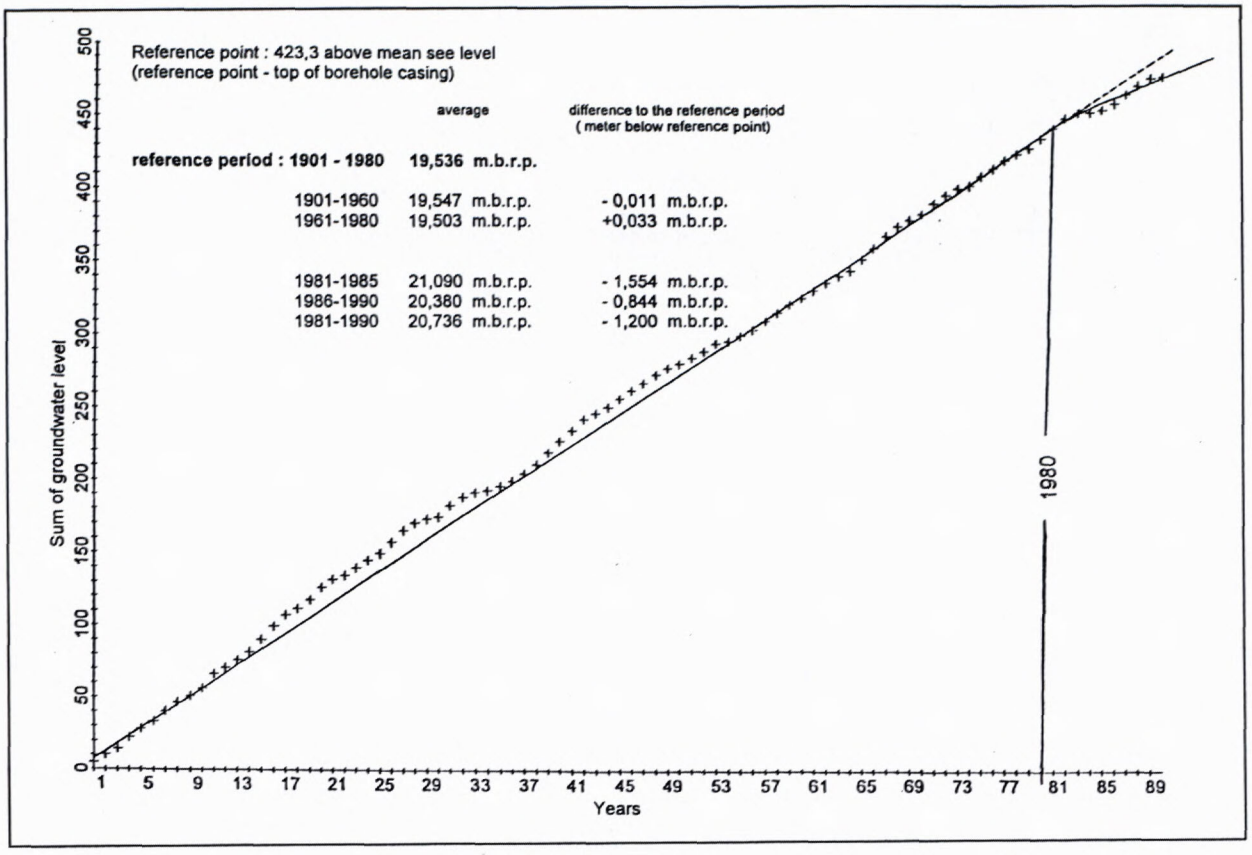


Fig. 5 Evaluation of groundwater level changes. Location: Banín, Svitavy country Czech Republic; Borehole no. V-12

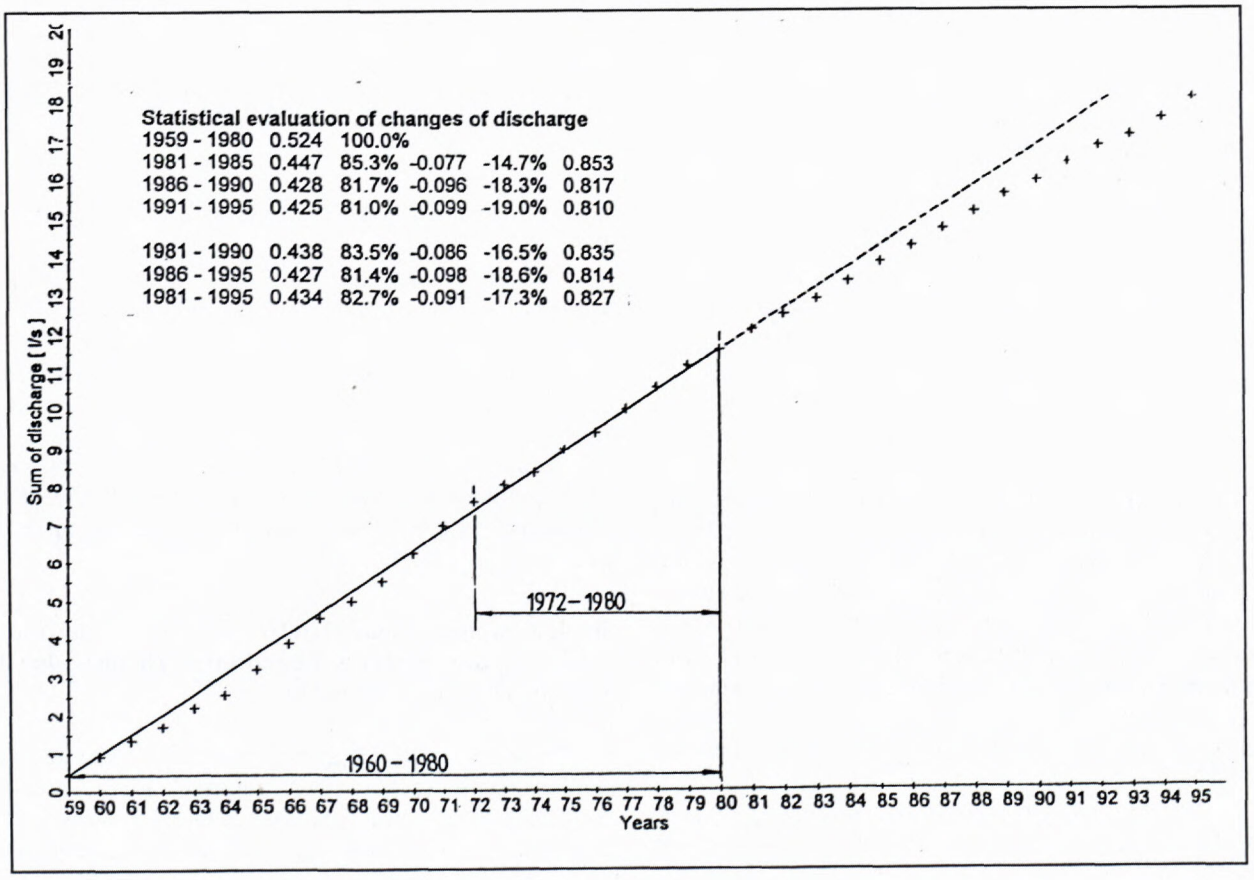


Fig. 6 Location: Revúcka vrchovina; I. D. No. of station: 1966; Station: Kyjatice - Prdlavka

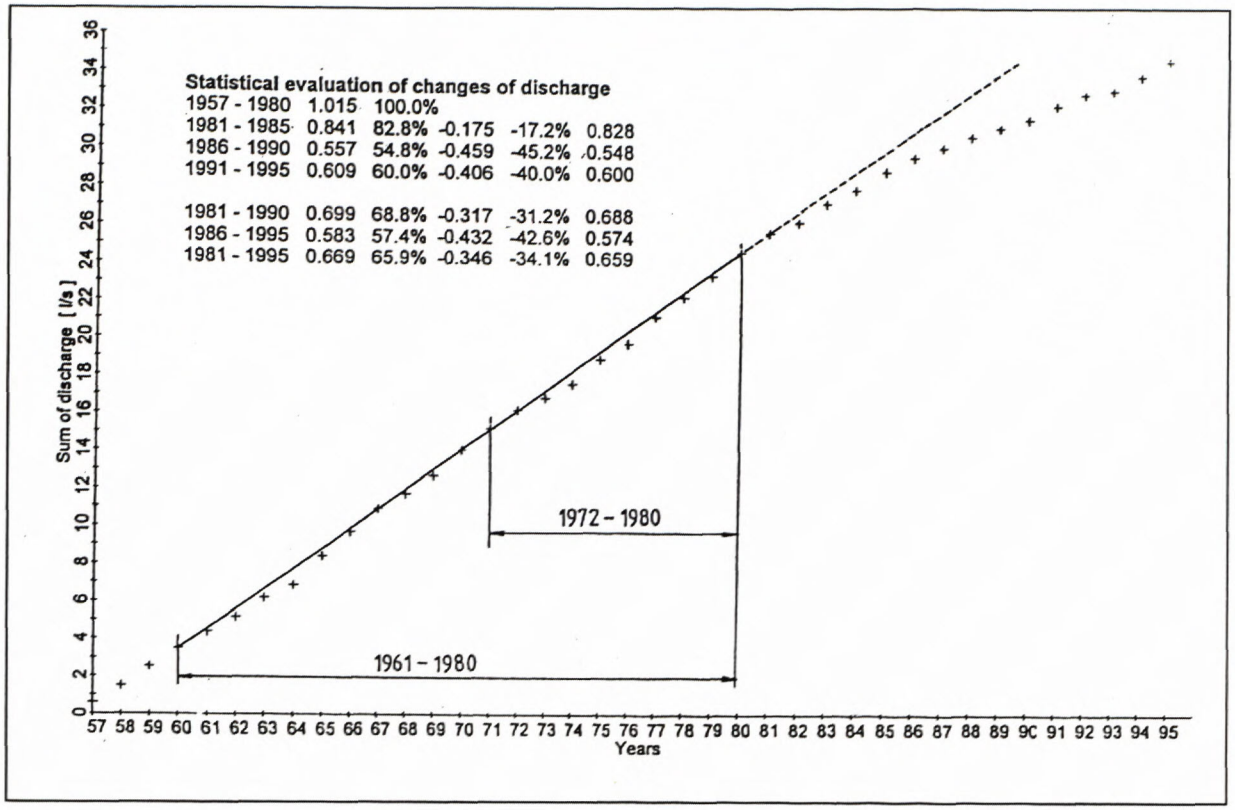


Fig. 7 Location: Slovenský kras; I. D. No. of station: 1901, Station: Gemerská Horka – Malá Studnička

In this solution it is built on the assumption of continual development of quantitative changes up to 2010 in agreement, as was the course of this development in the period 1981–1995. A mathematical programme was formed for the solution making use of a set of mathematical functions for the most probable prolongation of cumulative lines after 1995 in the connection with the previous influenced period. By means of this programme the supposed changes in groundwater resources in the year 2010 were enumerated (also the prognoses for the year 2005 were given in terms of these calculations).

Summary of data on the influenceof climatic changes on the groundwater resources and reserves

a) The performed evaluation documented significant negative quantitative changes in groundwater resources and reserves in the period 1981–1995 in the comparison with the period prior to 1981 on the greater part of Slovak territory. This decline in the groundwater resources was observed on majority of monitored springs as well as in the monitoring wells. An important decline of groundwater levels and also in groundwater storage was documented mainly in the south-western and southern parts of Slovakia.

b) These changes, in spite of the small area of Slovakia, show significant differences in time and space. From the point of view of time the period 1981–1985 comes out unequivocally as the period of the beginning of these changes, while the following two 5-years periods (1986–1990 and 1991–1995) are already the periods of vast decline changes. *The very fast beginning of these quantitative changes, which occurred practically during 5 years (in the period 1981–1985) is alarming.*

Throughout Slovakia the average changes in groundwater discharge in individual 5-year periods are: 1981–1985 by 6.7%; 1986–1990 by 19.5%; and 1991–1995 by 20.2%.

This means that at present (the average for the period 1991–1995 is considered as present) we have in Slovakia by an average of 20 % less groundwater resources than before the year 1981. In some parts of the Slovakia these declines are even higher. In an important part of southern Slovakia they even reach 40 % for the period 1986–1995. Moreover, for the period 1991–1995 groundwater levels in southern Slovakia were on the average 1.03 m lower than they were during reference period (Tab. 2).

Review of basic spacial differences in groundwater resources and reserves quantitative changes due to climatic changes in Slovakia

To give a review of basic differences of these changes in Slovakia the whole territory was divided into 5 regions, for which are given average values of quantitative changes in groundwater in percentage in the relation to the reference period.

The 5 regions are shown in Fig. 8 and Tab. 3.

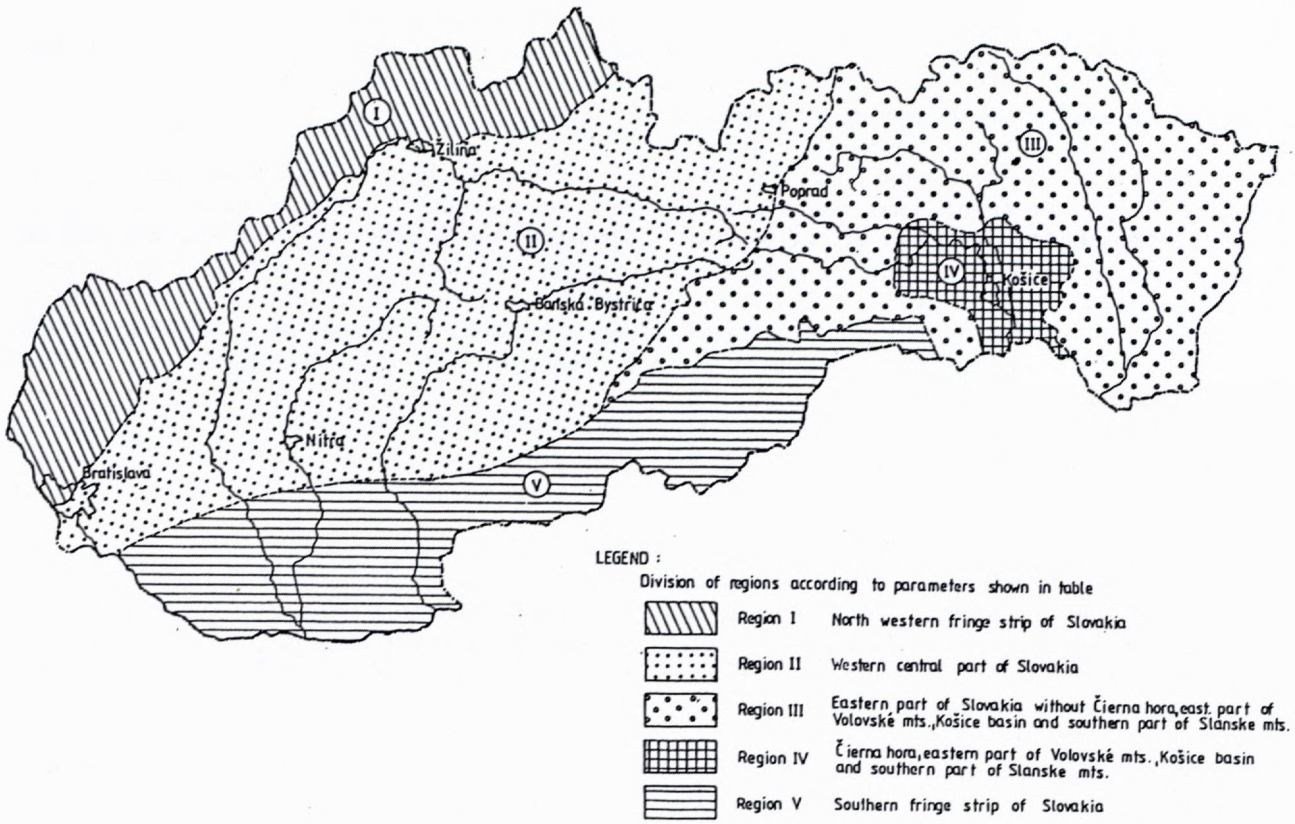


Fig. 8 Regional divisions of Slovakia based on the different impact of climate changes on groundwater resources

Table 2 Review of groundwater level changes in the southwestern and southern part of Slovakia during the period 1981–1995 compared to the reference periods

Evaluated Region	Monitoring wells Registration Nos.	Num. of Wells	Average groundwater level changes during individual 5 year periods and the whole period compared to the reference periods*			
			1981–1985	1986–1990	1991–1995	1981–1995
Podunajská pahorkatina	307, 543, 549, 552, 572, 806, 817 379, 380, 685	7	–0,446	–0,955	–1,261	–0,714
Podunajská rovina	834, 917, 925	3	–0,253	–0,298	–0,653	–0,402
Juhoslovenská kotlina	908, 927	3	–0,245	–0,779	–1,054	–0,392
Slovenský kras		2	–0,139	–0,590	–0,768	–0,499
*Reference periods are from the commencement of measurements up to 1981						

Table 3 Review of the average quantitative groundwater resources changes for the evaluated period 1981–1995 related to the reference period prior the year 1981

Region No.	Name of region	Number of evaluat. springs	Average quantitative changes as % of reference period			
			1981–1995	1981–1985	1986–1990	1991–1995
I.	North western fringe strip of Slovakia	9	–2,3	+2,8	+0,2	–9,8
	North western fringe without Chvojnica hills	7	+2,1	+5,7	–0,7	+3,1
II.	Western central part of Slovakia	31	–15,0	–7,4	–17,9	–19,9
III.	Eastern part of Slovakia without Čierna hora, east. part of Volovské mts., Košice basin and southern part of Slanské mts.	12	–19,4	–12,0	–23,3	–23,0
IV.	Čierna hora, east. part of Volovské Mts., Košice basin and southern part of Slanské Mts.	6	–0,2	–0,5	–0,6	+0,5
	Ditto, without southern part	5	–4,0	–5,7	–2,4	–4,8
V.	Southern fringe strip of Slovakia	15	–27,2	–9,4	–39,1	–33,1

Region I.

From the results in Tab. 3 it is evident that the least negatively quantitatively influenced groundwater resources in Slovakia due to climatic changes are in Region I which forms the north-western fringe belt comprising mountain ranges Malé Karpaty, Biele Karpaty, Javorníky and Stredné Beskydy. In this belt there were not found any significant quantitative changes in the evaluated period 1981–1995, on the contrary, there was a small increase in groundwater resources (by an average of 2.1 % higher yields in 1981–1995 compared with the reference period). This situation was caused by a significant increase of annual precipitation due to climatic changes by as much as 20 % roughly since 1979–1980, as shown by the cumulative diagram of annual precipitation for station Pernek and the cumulative diagram of average yields of the spring "Štôlna" in Pernek (Fig. 9 a). But this important increase of precipitation and its influence on the significant increase of groundwater yields was markedly reduced by other climatic influences (probably mainly by an increase of air temperature) with the significant presentation after 1987, which is documented by a double in groundwater resource availability, with certain time retardation - mainly in the period 1991–1995 (in the comparison both with the reference period and the period 1981–1990). The lowest average percentage declines were documented in this region in the area formed by the mountain ranges of Velká Fatra and Kremnické vrchy.

Region III.

In region III. – eastern Slovakia represented by the mountain ranges of Muránska planina, Slovenský raj, Havranie vrchy, Spišská Magura, Lubovnianská vrchovina and Vihorlatské vrchy there were also significant quantitative declines in groundwater resources. In the comparison with the western - central part of Slovakia (with region II.), this quantitative decline is even higher, but spatially more evenly distributed. In relation to the reference period the decline of groundwater resources was 19.4 % in the period 1981–1995. In individual 5-year periods it was: in 1981–1985 by 12.0 %; in 1986–1990 by 23.3 %; and in 1991–1995 by 23.0 %.

More detailed and extensive evaluations of 9 long-term sets of continual monitoring of spring yields in the mountain ranges of Slovenský raj and Havranie vrchy in region III., including also the results from hydrological years 1996–1997 (Kullman, 1998), documented the results in accordance with those received from the region as a whole, but they also proved a declining trend of groundwater resources also in the period 1996–1997 [average decline in the period 1996–1997 by 28.3 % in the single hydrological year 1997 even by 35.4 % in comparison with average values in the reference period].

Region IV.

In region IV. in the eastern Slovakia formed by the mountain range of Čierna hora, by the eastern part of Volovské vrchy, Košická kotlina and the southern part of Slánske vrchy there was documented lower negative influence (yield decline) caused by climatic changes in the mass curve of precipitation versus spring yields, Fig. 9 b, which filters the influence of precipitation and it documents the cumulative influence of other climatic factors.

Region II.

In region II. - in the western-central part of Slovakia there was a significant decline of groundwater resources documented on the basis of the most extensive collection of long-term monitoring (31 stations). In the relation to the reference period (up to 1981) there was documented an average decline of groundwater resources by 15.0 % in the period 1981–1995. In individual 5 - year periods it was a decline by 7.4 % in 1981–1985, 17.9 % in 1986–1990 and 19.9 % in 1991–1995 in the relation to the reference period. But in this region there are significant differences among individual mountain ranges or from site to site within a range. The highest average declines of groundwater resources were documented in this area in the mountain ranges of Vtáčnik, Tribeč, Nízke Tatry and Podtatranská kotlina. Moreover, in several mountain ranges of this area and that is mainly in Považský Inovec and Súlovské vrchy there was an extremely large decrease comparison with the region II., III. and V. If we disregard anomalous positive results in Slánske vrchy based on a single monitoring point, there was recorded in the other parts of this region a yield decline by an average of 4.0 % in the period 1981 - 1995 in comparison with the reference period (in individual 5 - year periods it was a decline by 5.7 %, 2.4 % and 4.8 %). In the comparison with other territories of the eastern Slovakia these yield declines are considerably lower. We cannot exclude that it may be the similar situation like in region I. Detailed judgement of the causes were not evaluated.

Region V.

Region V. includes the southern fringe belt formed by lowland areas of Podunajská rovina, southern part of Podunajská pahorkatina, Juhoslovenská kotlina, Revúcka vrchovina and the mountain range of Slovenský kras. In this southern fringe belt the highest and alarming quantitative declines of groundwater resources and reserves were unequivocally documented in the comparison with the reference period.

After a lower decline of groundwater resources in the evaluated first 5 - year period (by an average of 9.4 %), the following decade recorded the highest decline of groundwater resources in the territory of Slovakia on average, and that is 39.1 % and 33.1 % in the periods 1986–1990 and 1991–1995. For several groundwater resources these declines in the 1986–1995 decade are represented even by 40–50 % average decline of discharge in the comparison with the reference period. The significant decline in groundwater resources in this territory is also accompanied by a high and prevailingly constant decline of groundwater levels so that the groundwater sources, too. It is realistically characterised by an graduating of groundwater average levels decreasing according to the data from 15 monitoring wells (Tab. 2). In the comparison with average levels during the reference period prior 1981 an average decline of ground

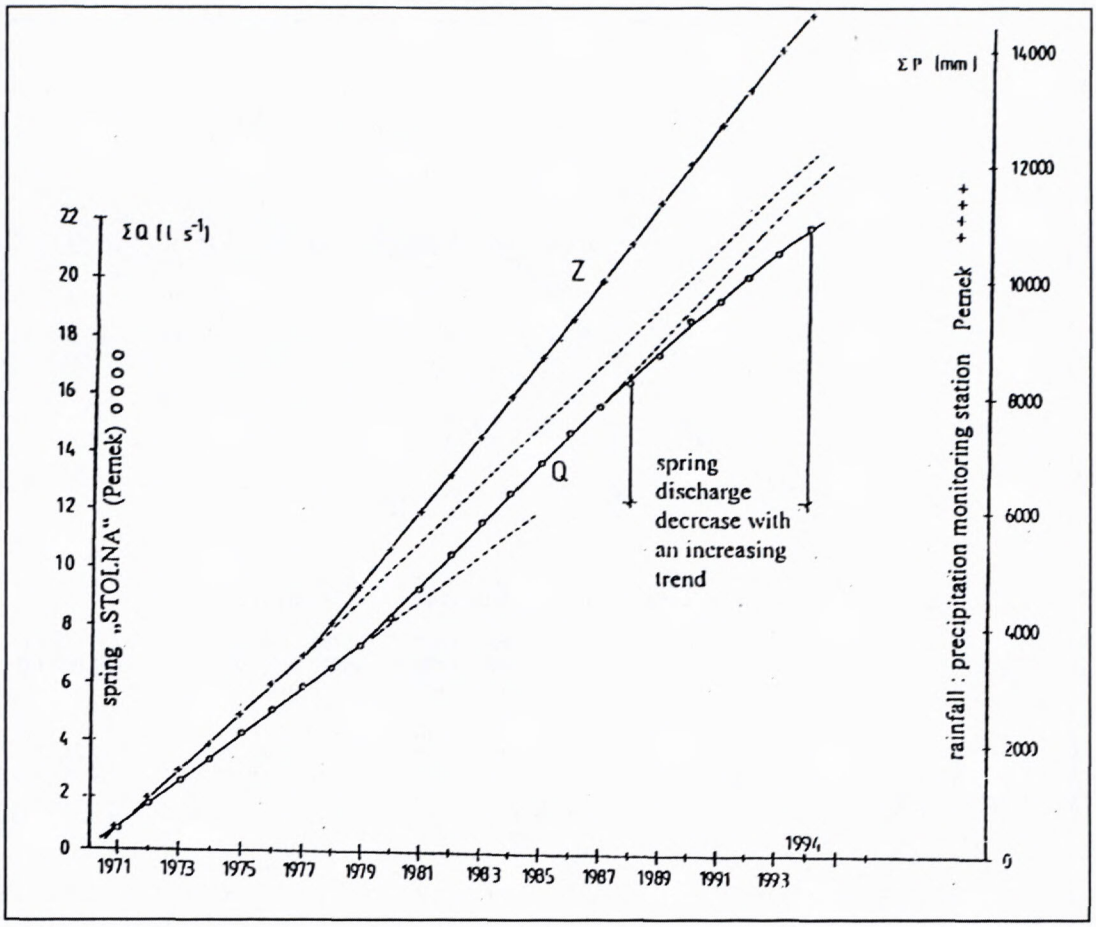


Fig. 9a Cummulative diagramme of the annual bulk precipitation at the precipitation station Pernek and cummulative diagramme of the mean annual discharge (Q) of the spring Stôlňa (Pernek, Pezinské Karpaty)

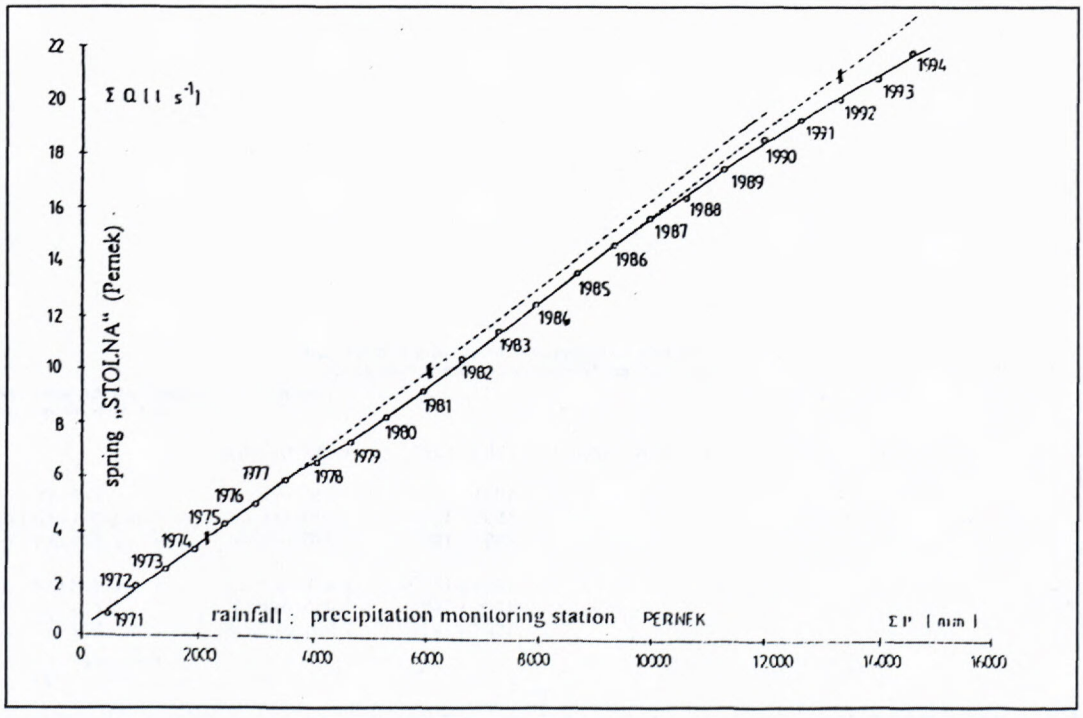


Fig. 9b Double mass curve of the annual bulk precipitation (station Pernek) and the mean annual discharge

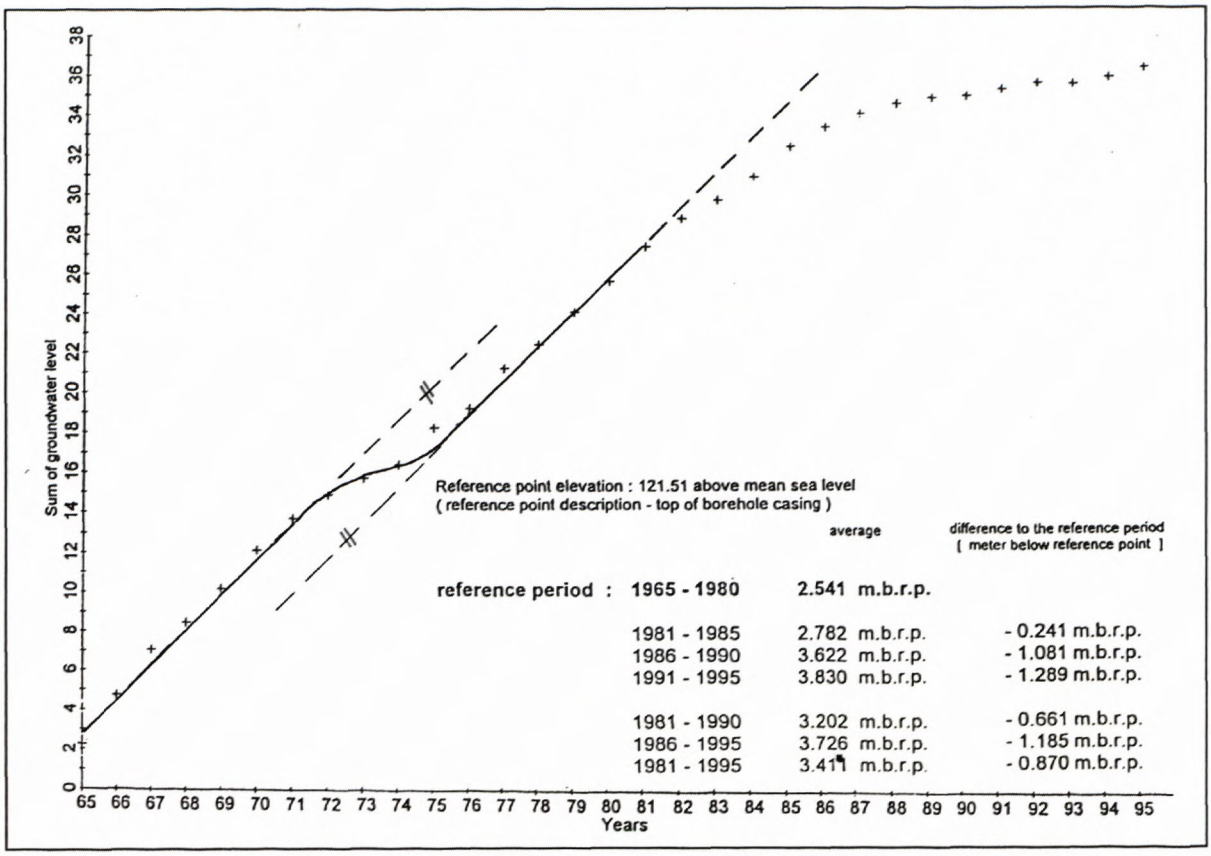


Fig. 10 Evaluation of groundwater level changes. Loc.: Podunajská pahorkatina, I. D. No. of station: 806, Station: Vyškovce nad Ipľom

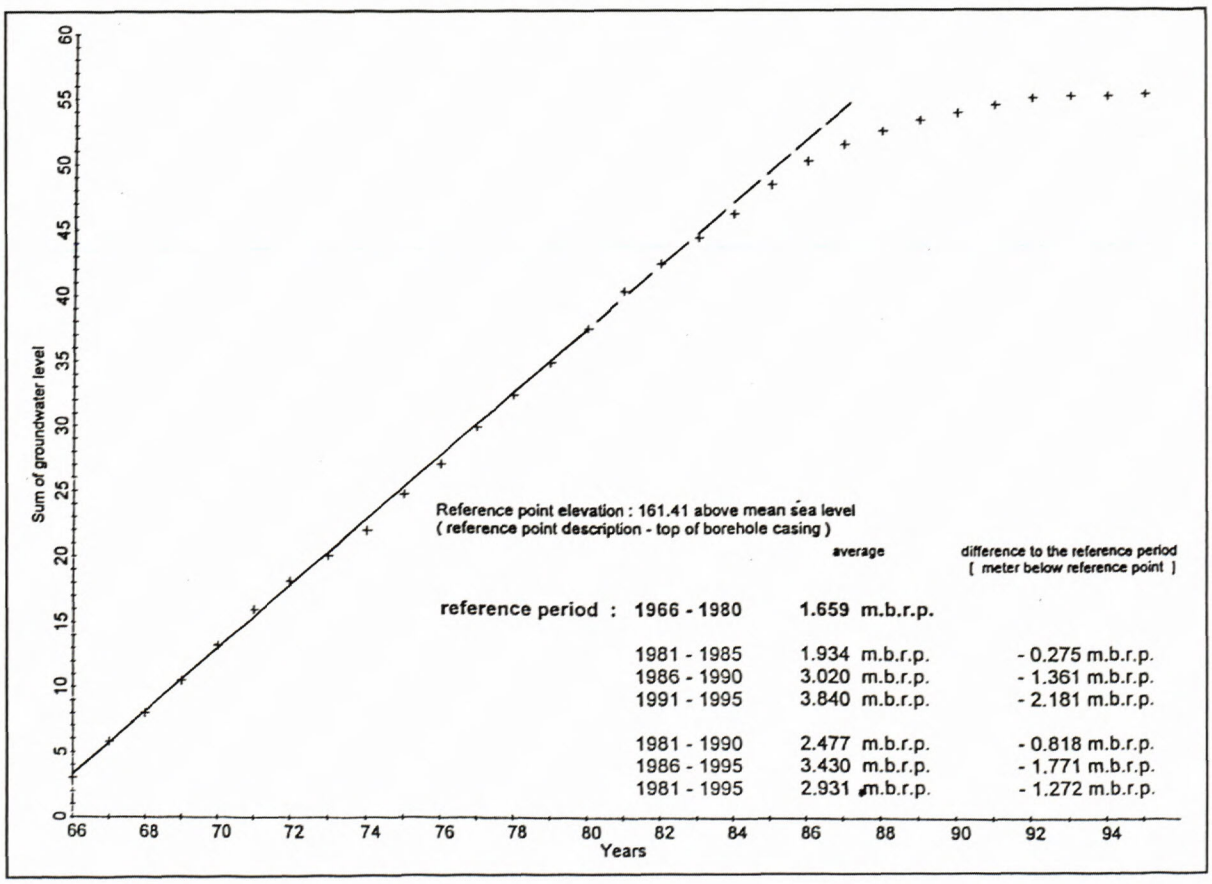


Fig. 11 Evaluation of groundwater level changes. Loc.:Juhoslovenská kotlina; I. D. of station:917, Station: Chanava

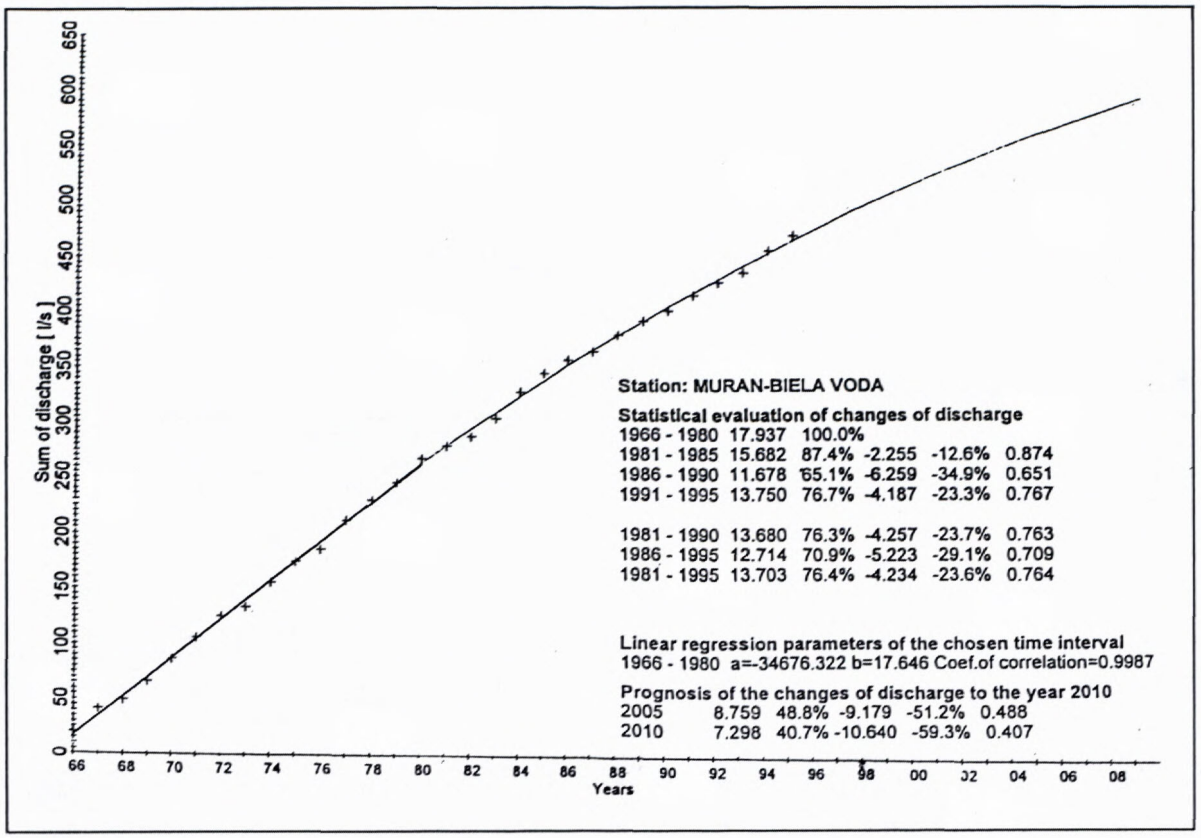


Fig. 12 Prognosis of the changes of discharge to the year 2010; Location: Muránska planina, I. D. No. of station: 1908, Station Muráň – Biela voda

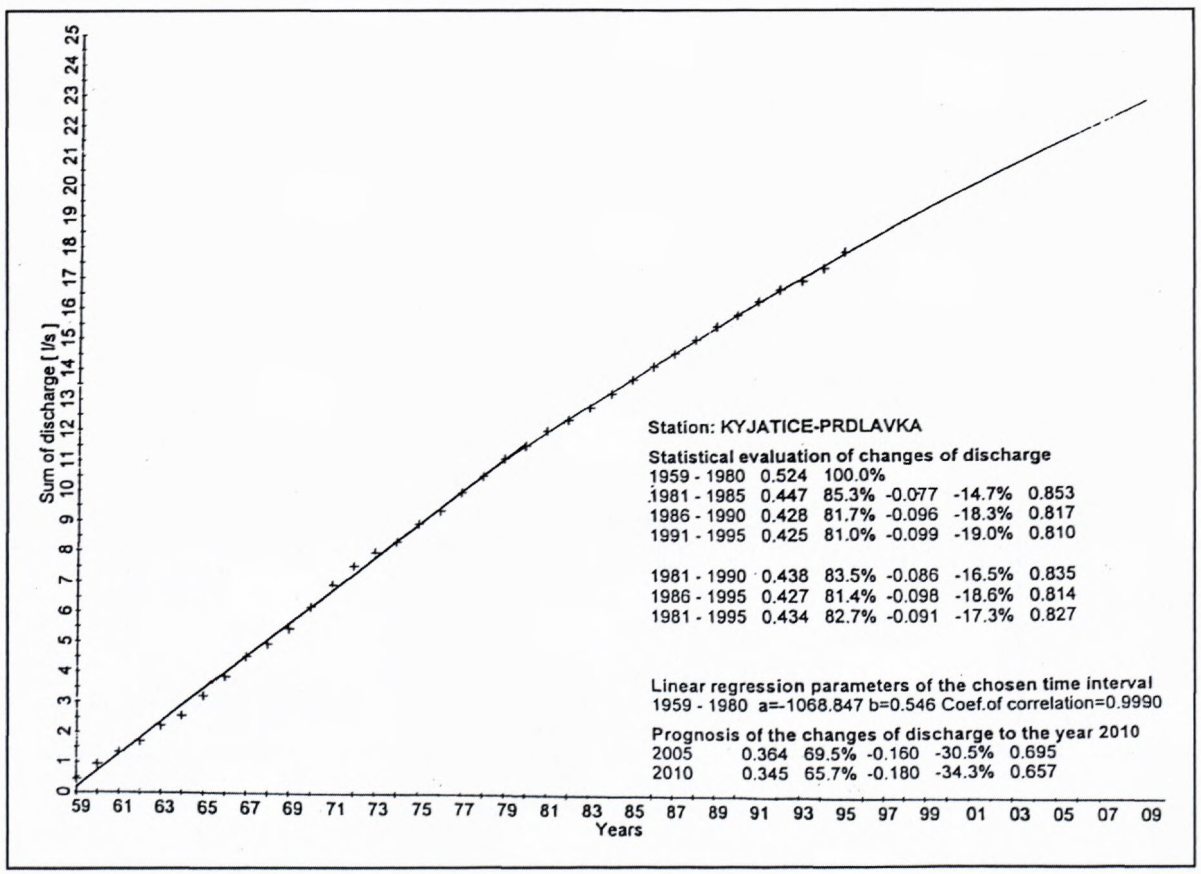


Fig. 13 Prognosis of the changes of discharge to the year 2010. Location: Revúcka vrchovina, I. D. No. of station: 1966, Station: Kyjatice–Prdlavka

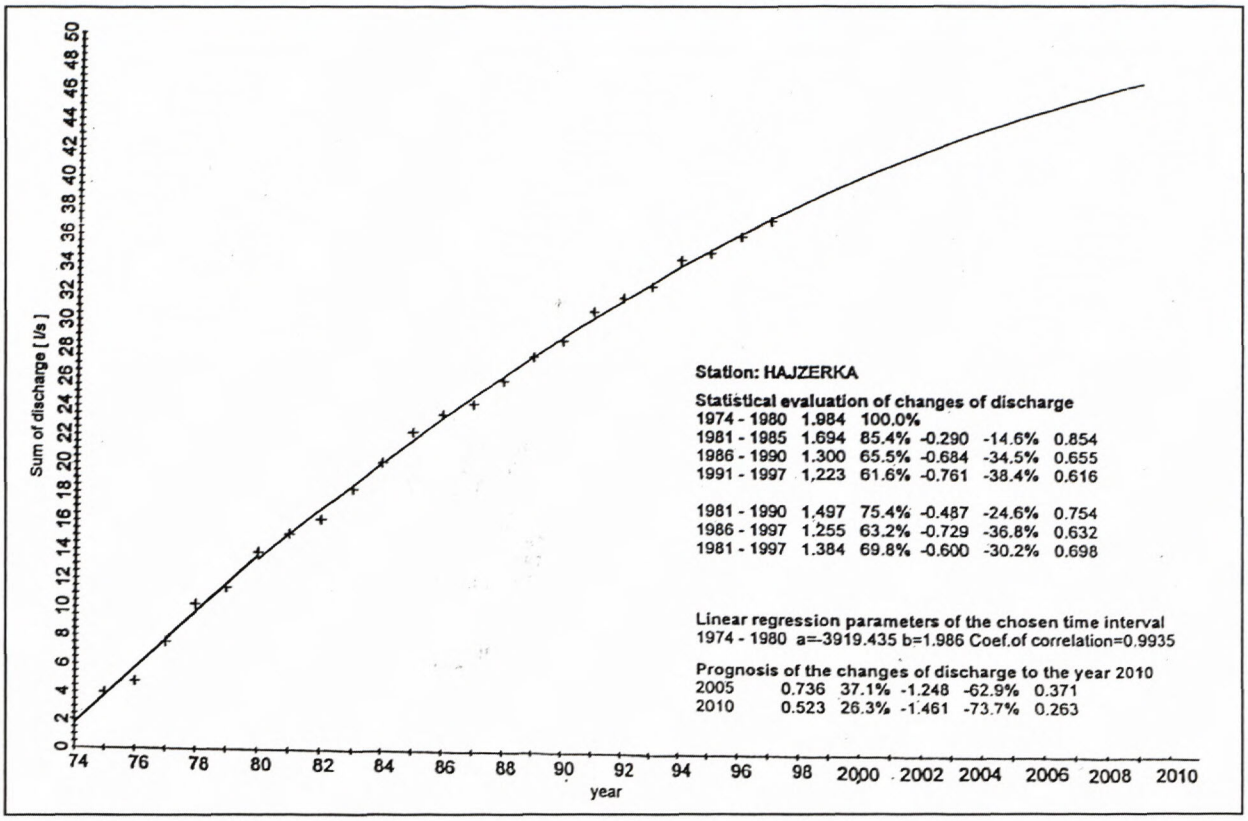


Fig. 14 Prognosis of the changes of discharge to the year 2010;.Location: Hnilecké vrchy; I. D. No. of station: 2162, Station: Nálepkovo „Hajzerka"

Table 4 Groundwater discharge changes prognosis for year 2010 compared to the mean discharges during the reference period (upto 1981) for a set representative springs

Region	Spring Registr. No	Location Spring name	Geomorphological region	Average quantitative change as % related to the reference period upto 1981 during periods		Prognosis for year 2010
				1981–1995	1991–1995	%
I	119	Plavecký Štvrtok "Bezedné"	Borská nížina	7,4	-6,9	18,0
I	113	Pernek "Štola"	Malé Karpaty	+19,1	+4,4	-1,3
II	1394	Podhorie "Handrlová"	Štiavnické vrchy	-16,8	-15,5	-33,0
II	320	Pribilina "Surový hrádok č.1"	Podtatranská kotlina	-18,7	-21,6	-52,0
III	1908	Muráň "Biela voda"	Muráňska planina	-23,6	-23,3	-59,3
III	2353	Jezersko "Pod svahom"	Spišská Magura	-26,5	-27,8	-33,2
III	2153	Dobšina "V Spišskom potoku 2"	Slovenský raj	-34,5 *	-43,6 **	-62,8
III	2154	Dobšina "Sedem prameňov"	Slovenský raj	-14,4 *	-29,4 **	-31,7
III	2162	Nálepkovo "Hajzerka"	Hnilecké vrchy	-30,2 *	-38,4 **	-73,7
IV	2282	Boliarov "Rybníček"	Košická kotlina	-1,1	+6,9	-2,0
V	1966	Kyjatice "Prdlavka"	Revúcka vrchovina	-17,3	-19,0	-34,3
V	1467	Kamenín "Studená studňa"	Podunajská pahorkatina	-13,8	-32,4	-90,2
V	1901	Gemerská Hôrka "Malá studnička"	Slovenský kras	-34,1	-40,0	-93,3
V	2032	Jablonov nad Turnou "Koszoru"	Slovenský kras	-14,9	-24,1	-76,0

Note: *1981-1997, **1991-1997

water levels by 0,326 m was documented in the period 1981–1985, in the period 1986–1990 it was by 0.740 m (an increase in the decline of groundwater levels by 0.414 m) and in the period 1991–1995 it was by 1.032 m (an increase in the decline of groundwater levels by 0.292 m). *On the one hand it is documented by a constant decline of groundwater levels in the period 1981–1995 and on the other hand by the fact that in the period 1991–1995 groundwater levels in this region were by an average of 1.032 m lower than the average groundwater levels up to 1981 (reference period).* Unequivocally it is characterised by the cumulative diagrams of average annual levels in the observed period. For an illustration we present cumulative lines from two long-term sets of continual monitoring of groundwater levels from this region (Fig. 10 and 11). It confirms an important decline in groundwater resources as well as a significant negative impact on several other spheres of the national economy (forestry and agriculture, ecology etc.).

Prognosis of quantitative development of groundwater resources up to 2010

As it was already introduced, a part of the evaluation is also the presentation of an assumed prognosis of quantitative changes of water resources after the year 1995 continuing accordingly with the changes in the period 1981–1995. Even though some errors cannot be excluded, it is necessary to take these results into consideration as one of the possibilities in the development of quantitative changes.

Selected long-term data sets of continual spring yield monitoring representative for the whole territory of Slovakia were evaluated (the sets with a small influence as well as the sets with a large influence by climatic changes). The results of this evaluation using methods presented in Chapter 3, are given on Tab. 4. The graphic results of three data sets are presented as examples (Fig. 12, 13, 14).

The results in the Table 4 lead to the possible conclusion that if the impact of climatic changes on the groundwater resources has a continuing negative trend, as it was inferred for the period 1981-1995, in the year 2010 we can expect the decline in yields of natural as well as exploitable groundwater resources in the comparison with their average discharge up to 1981 by an average of 50 %. In the regions which are most influenced by climatic changes (mainly in the southern fringe belt of Slovakia) this decline can reach, alternatively, even go beyond as much as 70 %.

Though we hope that the reality will be perhaps more optimistic than the one presented by this prognosis, it is necessary with regards to the present situation, based on extensive studies of the available data, to take this possibility into consideration and to take preliminary measures to diminish their possible negative impacts on water management, as well as on other spheres of our national economy.

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